

Performance Analysis of a Closed Loop Single Slope Solar Still (CLSSS) Plant

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Abstract- In this study, the authors propose a closed-loop single slope solar still (CLSSS) plant. The primary aim is to develop an affordable, small-sized solar distillation plant that provides a reasonable amount of potable water for small communities, fulfilling their drinking water needs. The mathematical model of the proposed system has been developed and validated through experimentation. The performance of the plant was computed for Jodhpur, India (26°14'20.21"N and 73°1'27.51"E). This proposed plant outperforms conventional single slope solar still (SSSS) plants. For a 16m² (4x4) plant, the daily distillate output in May and January is 122.3 L and 55.7 L, respectively. The output distilled water is 54.4% higher in May and 72.2% higher in January compared to the conventional SSSS plant. The proposed plant produces a total annual output of 25,528 L, approximately 60.9% more than the conventional SSSS plant. Additionally, the study finds that the mass flow rate (MFR) of water has very little effect on the distillate produced. The cost of water produced ranges from Rs 0.30/L (0.0036 US\$) to Rs 0.70/L (0.0085 US\$), with a payback period between 70 to 151 days.

Keywords Closed loop Single slope solar still plant (CLSSS), Additional reservoir, Thermal performance, Economic analysis, Mass flow rate (MFR), Solar still (SS).

1. Introduction

Water is crucial for the growth of economies and the well-being of nations. Clean drinking water is vital for humans and all living creatures. Additionally, industries and agriculture rely on fresh water for various purposes [1]. Nearly 70% of the world's surface is covered by water, amounting to 1.4 billion km³, of which 97.5% is salt water. Only 0.5% of the freshwater is accessible and usable to support all life on Earth [2]. The demand for clean, pure water is rising dramatically in response to global population growth and industrialization [3]. At the same time, due to deforestation, there is an imbalance between the supply and demand of pure water, raising concerns among researchers about water accessibility in the future. One of the crucial processes for turning salty or dirty water into potable water is desalination. Most desalination methods depend on conventional fuel, which has negative effects on the environment, nature, and human health [4]. The finest alternative technique that is easy to use and environmentally benign is solar desalination [5]. Using solar energy, brackish water is desalinated to provide pure drinking water by removing salts. The solar desalination process is carried out using the solar still.

SS is a device used for solar distillation. The impure water in a solar still's basin is heated by solar radiation that passes through the glass cover. The water evaporates and condenses on the bottom of the glass, dissipating heat into the environment. The interior of the still has collecting troughs where the fresh water film on the glass falls. The most basic design of solar still is single slope solar still (SSSS) or single basin solar still the design is simple, inexpensive, and requires little maintenance, but it produces less output [6,7]. Numerous scholars have tried to enhance the production output of SSSS. As a result of these efforts, numerous unique SS designs have been created, such as double slope SS [8-10], multiple basin (multi-effect or multi-stage) solar stills [11-13], weir type SS [14-16], stepped SS [17-20], inverted trickle SS [21], inclined SS [22-23] which provide a higher yield than the traditional SSSS. Various researchers have worked to improve the efficiency of solar stills by integrating other solar thermal systems, such as flat plate solar collectors [24-27], evacuated tube collectors [28-31], parabolic concentrators [32-34], solar stills with solar ponds [35-36], etc. Different top cover shapes, including spherical [37], hemispherical [38-39], V-type [40], triangular prism [41], pyramidal (triangular and square) [42-46], conical [47], and tubular [48,49] were tried in SSs as part of innovative research in this area to increase the solar energy incident as well as productivity of SSs using fins on the absorber plate [50-52] increases the rate of

evaporation there by increases the output of SS. Energy storage materials (sensible and latent) [51-56] can also increase the daily output of solar stills. Solar energy can still be used during times when solar energy is not available by using heat storage materials.

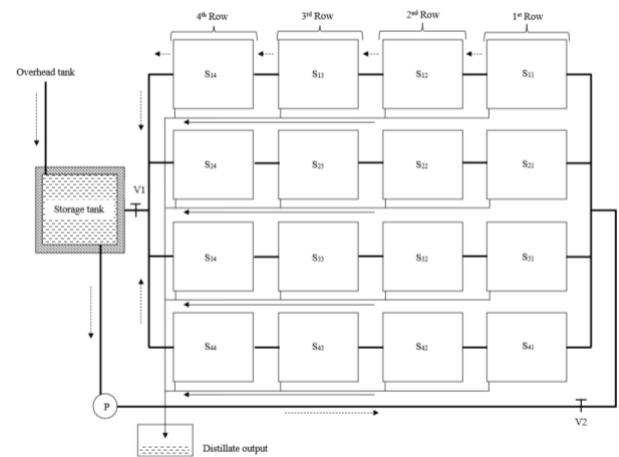
According to the findings, different SS designs provided a range of results, making it difficult to optimize a SS's design using the data. According to the reviewer's recommendation, a multi-basin SS should have a minimum of three basins in order to produce the most energy [57]. According to evaluation of several domestic solar still designs, the maximum yield that could be produced is roughly 12.48 l/m² per day, and it is for the hybrid system connected with evacuated solar water heater. The maximum thermal efficiency attained varies between 17.4 and 45%. [58].

Temperature difference between the cover and water in basin is the main operating factor for getting yield from still. Rate of water evaporation increases when the water temperature in basin is more, thus helps to enhance the output from still. Integrating the SSSS with flat plate collector enhances the production output of SSSS. Flat plate collector continuously provides hot water in still basin, this helps to increase the production output from solar still. It is seen that the output was enhanced about 60% by integrating SSSS with flat plate collector [26]. By connecting SSSS with solar shallow pond, the output was enhanced about 52.36% [59]. Although, integrating external heating source with solar still enhances the amount of pure water but the additional cost of the device increases the overall cost of water produced. To address this issue Sodha et al. [60] proposed to utilize the waste hot water coming from industries, with hot water input to the SSSS the production increased significantly. Mishra et al. [61] later on experimentally validated the proposed model and analyzed the performance of SSSS fed by waste hot water coming from power plant. Although this idea seems to be a reasonably good option to fulfil the drinking water demand, and is more cost effective but still the availability of hot water at a particular place is a biggest constraint with this method. Recently Somwanshi & Shrivastava [62] proposed closed loop inclined wick solar still (CLIWSS) which operates in closed cycle to provide continuous hot water as feed in SS. They proposed to have water flowing through the solar still into an insulated water reservoir. The hot water from exit of SS is pumped back to SS. They found an enhancement in the output of CLIWSS by 115% (May) over conventional inclined wick solar still.

The present work is an extension of the previous work proposed by Somwanshi & Shrivastava [62]. In this work authors proposed a small-scale solar distillation plant (16m²) which contains additional hot water reservoir. The whole plant operates in closed loop. The plant contains SSSSs arranged evenly in rows and columns (4x4) the last row is connected through a common distribution insulated pipe with an insulated reservoir. Water from reservoir is pumped into another distribution pipe through which water is evenly distributed to all the SSs in the first row of the distillation plant. Water, travels in consecutive rows and finally collected in the additional water reservoir placed at the exit of the last row. Water after traversing through the

basin of SSs kept in different rows gets heated due to the solar radiation absorbed through glass cover of SSs. During sunshine hours the temperature of the water is highest at outlet from the last row of distillation plant. The hot water from exit of distillation plant is stored in reservoir and further fed into the SSs kept in first row of plant (Fig.1). With hot water as inlet to SSs the overall output is expected to get enhanced. The hot water from reservoir is continuously pumped into the solar stills in series and parallel, the whole system works in closed cycle and provides continuous hot water flows into the solar stills.

In this work, the authors presented a mathematical model of this design. The model has been validated by experiment. The effect of MFR of water has been analyzed. The effect of increasing the number of rows of the distillation plant has been further analyzed in this work. Numerical computations have been performed to determine the hourly, monthly and



annual distillate output produced by the plant for the hot climate of Jodhpur, India. A techno-economic analysis has been performed to find water cost (Cost/L) of water produced and the payback period of the plant.

Fig.1. Schematic diagram of proposed plant.

(S_{ab} = represents solar still where a=number of rows, b=number of columns, V1=V2= Valves, P= Pump)

2. Methodology

Various steps followed in this work are given below in Fig.2

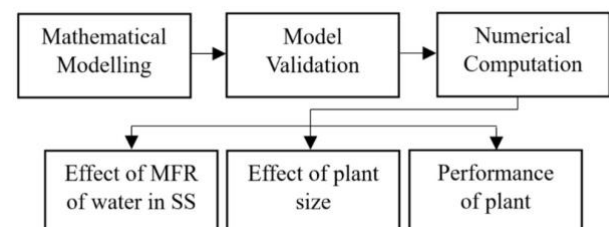


Fig.2. Methodology of this work.

2.1. Mathematical Modelling

Following assumptions have been considered while writing energy balance equations.

- The heat capacity of the glass has been neglected.
- The inclination angle of solar still is (20°- 21°) equal to latitude of place.
- The solar distiller unit is completely sealed vapor - leakage proof
- Temperature loss of water when flowing through a pipe is taken as $\approx 1^\circ\text{C}$.
- The quantity of fresh water poured into the reservoir matches the amount of water that evaporates from the SSs.
- Correlations used for determining convective, radiative and evaporative heat transfer coefficients have been referred by [1]

Considering single solar still of the plant,

Energy balance for glass

$$\alpha_g S(t) + h_1(T_w - T_g) = h_2(T_g - T_a) \quad (1)$$

In Eq.1 h_1 and h_2 are given by,

$$h_1 = h_{ci} + h_{ri} + h_{ei} \quad (2)$$

$$h_2 = h_{co} + h_{ro} \quad (3)$$

$$h_{ci} = 0.884 \left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 P_w} \right]^{1/3} \quad (4)$$

$$h_{ei} = 16.273 \times 10^{-3} \times h_{ci} \frac{P_w - P_g}{T_w - T_g} \quad (5)$$

Saturated vapor pressure will be,

$$P = \exp \left[25.317 - \frac{5144}{T + 273} \right] \quad (6)$$

$$h_{ri} = \varepsilon_{eff} \sigma [(T_w + 273)^2 + (T_g + 273)^2] (T_w + T_g + 546) \quad (7)$$

$$\varepsilon_{eff} = \left[\frac{1}{\varepsilon_g} + \frac{1}{\varepsilon_w} - 1 \right]^{-1} \quad (8)$$

$$h_{co} = 2.8 + 3v_a \quad (9)$$

$$h_{ro} = \varepsilon_g \sigma \frac{[(T_g + 273)^4 - (T_a + 267)^4]}{(T_g - T_a)} \quad (10)$$

From Eq.1,

$$T_g = K_1 + K_2 T_w \quad (11)$$

Here constants

$$K_1 = \frac{\alpha_g S(t) + h_2 T_a}{h_1 + h_2} \quad (12)$$

$$K_2 = \frac{h_1}{h_1 + h_2} \quad (13)$$

Energy balance of water in basin of SS, considering small element dx (Fig.3)

$$\rho_w (ddx) \delta c_w \frac{\partial T_w}{\partial t} + \dot{m}_w c_w \frac{\partial T_w}{\partial x} dx = (ddx) h_3 (T_b - T_w) - h_1 (ddx) (T_w - T_g) \quad (14)$$

Energy balance equation of basin liner will be,

$$\alpha_b S(t) = h_3 (T_b - T_w) + U_b (T_b - T_a) \quad (15)$$

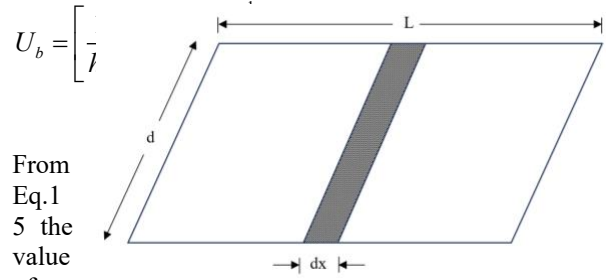


Fig.3. Section showing 'dx' strip of water in basin

$$K_3 = \frac{\alpha_b S(t) + U_b T_a}{h_3 + U_b}$$

$$K_4 = \frac{h_3}{h_3 + U_b}$$

From Eq. 11, 14 and 16, we have

$$\frac{\partial T_w}{\partial x} + A \frac{\partial T_w}{\partial t} + B T_w = C \quad (17)$$

In Eq. 17 the value of constants A , B and C will be given by,

$$A = \frac{d \delta c_w \rho_w}{\dot{m}_w c_w}$$

$$B = \frac{h_3 d + h_1 d - h_3 d k_4 - h_1 d K_2}{\dot{m}_w c_w}$$

$$C = \frac{h_3 d K_3 + h_1 d K_1}{\dot{m}_w c_w}$$

Eq. 17 can be solved by using following transformations [63]

$$x + \frac{t}{A} = \varepsilon$$

$$x - \frac{t}{A} = \eta$$

We can write.

$$\frac{\partial T_w}{\partial x} = \frac{\partial T_w}{\partial \varepsilon} \cdot \frac{\partial \varepsilon}{\partial x} + \frac{\partial T_w}{\partial \eta} \cdot \frac{\partial \eta}{\partial x} \quad (18)$$

Eq.18 can be given by,

$$\frac{\partial T_w}{\partial x} = \frac{\partial T_w}{\partial \varepsilon} + \frac{\partial T_w}{\partial \eta} \quad (19)$$

$$\frac{\partial \varepsilon}{\partial x} = 1, \frac{\partial \eta}{\partial x} = 1$$

$$\frac{\partial T_w}{\partial t} = \frac{\partial T_w}{\partial \varepsilon} \cdot \frac{\partial \varepsilon}{\partial t} + \frac{\partial T_w}{\partial \eta} \cdot \frac{\partial \eta}{\partial t} \quad (20)$$

$$\frac{\partial T_w}{\partial t} = \frac{\partial T_w}{\partial \varepsilon} \cdot \frac{1}{A} - \frac{\partial T_w}{\partial \eta} \cdot \frac{1}{A}$$

$$\frac{\partial \varepsilon}{\partial t} = \frac{1}{A}, \frac{\partial \eta}{\partial t} = -\frac{1}{A}$$

From Eq. 19, 20 and 17 we have

$$\frac{\partial T_w}{\partial \varepsilon} + \frac{B}{2} T_w = \frac{C}{2} \quad (21)$$

Solution of Eq.21 will be, when subjected to boundary condition

At $t=0$, $T_w = T_{w0}$, $x=0$, $t=0$

$$T_w = \frac{C}{B} [1 - \exp\{-\frac{B}{2}(x)\}] + T_{w0} \exp\{-\frac{B}{2}(x)\} \quad (22)$$

Eq. 22 will give the value of temperature of water flowing at a particular time and space coordinate on substituting the value of solar radiation incident and ambient temperature at that instant of time. T_{w0} is the initial water temperature at $t=0$, by substituting $x=L$ we can get the temperature of water at exit of SS. (For front row $x=L_1$).

Average water temperature will be given by,

$$\bar{T}_w = \frac{1}{L} \int_0^L T_w(x) dx \quad (23)$$

By Eq. 22 & 23 we have

$$\bar{T}_w = \frac{C}{B} [1 - \frac{\{1 - \exp(-\frac{B}{2}L)\}}{BL}] + T_{w0} \frac{\{1 - \exp(-\frac{B}{2}L)\}}{BL} \quad (24)$$

In Eqs. 22 and 24 the initial inlet temperature of water into the solar still (1st row) $x=0$ is equal to tank water temperature the heat loss in pipe ($\approx 1^\circ\text{C}$)

$$T_{w0} = (T_{wt} - 1^\circ\text{C})$$

The distillate produced by single still (per hour) will be given by,

$$\dot{m}_{ewh} = \frac{h_{ei} A_c (\bar{T}_w - T_g)}{L_v} \times 3600 \text{ kg} / \text{m}^2 \text{h} \quad (25)$$

The distillate produced from a SS per second will be

$$\dot{m}_{ews} = \frac{h_{ew} A_c (\bar{T}_w - T_g)}{L_v} \text{ kg} / \text{m}^2 \text{s} \quad (26)$$

Energy balance equation of water reservoir will be,

$$M_{wt} c_w \frac{dT_{wt}}{dt} = \dot{Q}_u - \dot{Q}_m - \dot{Q}_T - \dot{Q}_s - \dot{Q}_b \quad (27)$$

In Eqn.27, first term of RHS is the rate of heat added by total number of SSs in the last row of plant, second term is heating rejection rate by adding make-up water. Third, fourth and fifth term are the rate of heat loss from top, sides and bottom of the tank.

$$M_{wt} c_w \frac{dT_{wt}}{dt} = n_s \dot{m}_w c_w (T_{w1n} - T_{wt}) - m_m c_w (T_{wt} - T_a) - U_t A_t (T_{wt} - T_a) - U_s 4 A_s (T_{wt} - T_a) - U_b A_b (T_{wt} - T_a) \quad (28)$$

For distillation plant n_s is number of stills in last row of plant, for 16m^2 plant (4×4) the value of n_s will be taken as 4 Eqn. 26 can be written as,

$$\frac{dT_{wt}}{dt} + X_1 T_{wt} = X_2(t) \quad (29)$$

Solving Eqn. 29, we have

$$T_{wt} = \frac{X_2}{X_1} \{1 - \exp(-X_1 t)\} + T_{wt0} \exp(-X_1 t) \quad (30)$$

In Eq.30, T_{wt0} is the initial tank water temperature and it is equal to tap water temperature taken as 20°C for Raipur climate.

In Eq.28 the values of constants X_1 and X_2 will be given by,

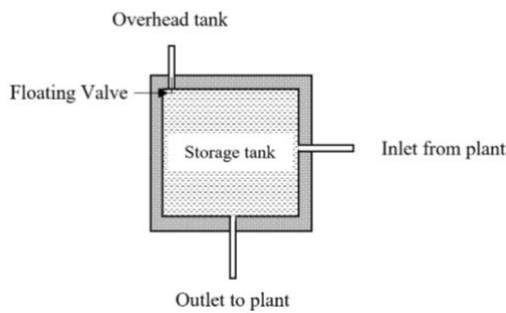
$$X_1 = \frac{n_s m_w c_w + m_m c_w + U_t A_t + U_s 4 A_s + U_b A_b}{M_{wt} c_w} \quad (31)$$

$$X_2(t) = \frac{n_s m_w c_w T_{w1n} + T_a (m_m c_w + U_t A_t + U_s 4 A_s + U_b A_b)}{M_{wt} c_w} \quad (32)$$

From Eq. 22, exit water temperature from SS can be determined, for the proposed plant. In Eq. 28 T_{wt_n} is the temperature of exit water coming from n^{th} row of the plant for 4×4 plant $n=4$. For a given climatic conditions the output produced and the exit water temperature from different SSs kept in a row will be same. The temperature of exit water from n^{th} row will be equal to temperature of inlet water for $(n+1)^{\text{th}}$ row. The hourly distillate output produced from SSs is computed From Eq. 25, the transient temperature of water in reservoir can be determined by Eq.30. The output produced by plant can be determined by adding the distillate output produced by SSs kept in different rows of plant.

2.2. Description of Proposed Plant

Proposed plant contains equal number of SSSS kept in series and parallel. To allow water flow through stills piping arrangement has been made. The last row of SS is connected to an insulated water reservoir. Water from reservoir is pumped into a common distribution pipe and fed evenly to different SSs kept in the first row. The exit water from the last row of SSs is collected in another distribution pipe and finally collected into the reservoir. Setup works in a closed cycle to continuously feed water (hot) from reservoir into the different SSs. The schematic of the proposed plant has been shown in Fig.1. To control the mass flow rate of water (MFR) into the SS's a valve has been provided with inlet pipe. The size of the plant (number of SSs in rows and column) depends on the area available as well as the requirement of drinking water. In present work we considered a small plant of area $16\text{m}^2 (4 \times 4)$ total 4 stills are kept in series and 4 in parallel. The size of additional water reservoir is taken equal to the number of SSs kept in first row and the amount of water stored in pipes. The depth of water kept in SSs is kept uniform by providing inlet pipe in bottom and the outlet pipe at a required water depth in SS (Fig.4). In this work we have considered the depth of water in SS's as 0.5cm the amount of water in a SS is 5kg . The capacity of the additional reservoir is taken as 24L (4L in pipes). The reservoir is connected with overhead tank and a floating valve is provided inside reservoir to keep water in tank uniform (Fig.4). A pump (20W) is provided to pump water into the SSs. Another pipe line is provided to collect the distillate from SSs into a distillate storage tank.



(b)

Fig.4. Piping arrangement in solar still and reservoir

2.3. Experimental Validation

To validate the proposed model an experiment was performed considering two single slope solar stills connected in series. The photograph of the experimental setup is shown in Fig. 5. The theoretical water temperature, temperature of glass cover, exit water temperature in different stills have been determined at a time interval of one hours. The theoretical readings have been compared by corresponding experimental readings. Experiment was performed at Raipur (21°14'40"N and 81°37'50"E) in a typical day 21/3/23. Hourly ambient temperature and solar radiation during

(a) flowing through SSs was 0.0032kg/s. details of various instruments used during experiment was given in Table 1.



Fig.5. Photograph of experimental setup

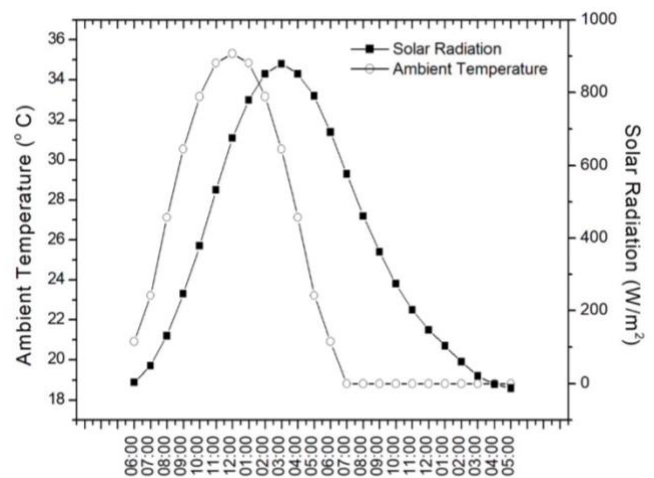
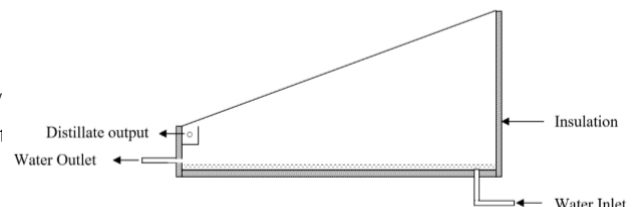


Fig.6. Hourly ambient temperature and solar radiation during experiment

Table 1. Details of various instrument used during experiment

Instrument	Range	Accuracy	Uncertainty
Temperature sensor K type- constantan	0°C to 150°C	±0.2°C	2% to 0.4% (10°C to 50°C)
RTD- Platinum temperature sensor	-50°C to 199.9°C	±0.1°C	1% to 0.2% (10°C to 50°C)
Digital anemometer	0.0m/s to 45.0m/s	±0.1	
Pyranometer (Kipps and Zenon)	0W/m ² to 1500W/m ²	73μV/ (Sensi	
Stop watch	-	±0.01s	-



experiment is shown in Fig. 6. The size of the additional reservoir during experiment was taken as 12L, initial water temperature in basin, glass cover temperature and initial temperature of tank water was recorded as 21.5° C, 18.6° C and 21.2° C, respectively. The mass flow rate of water

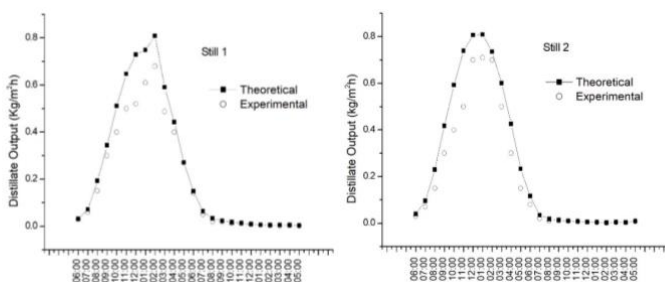
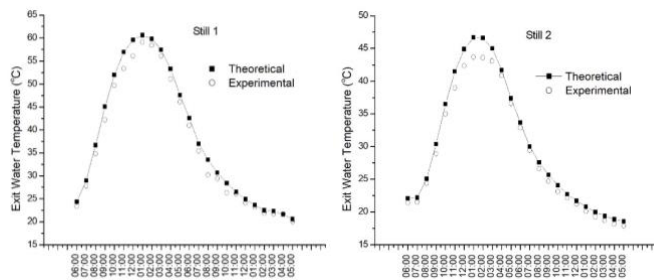
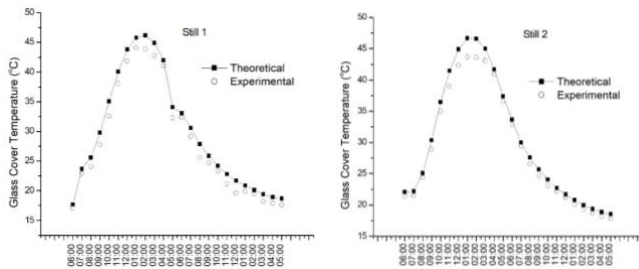
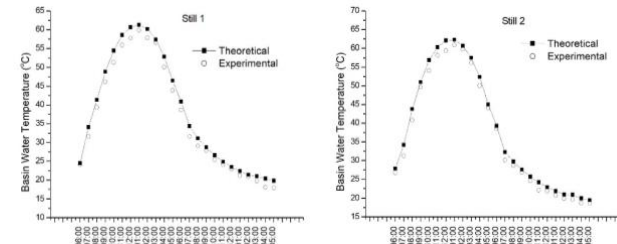
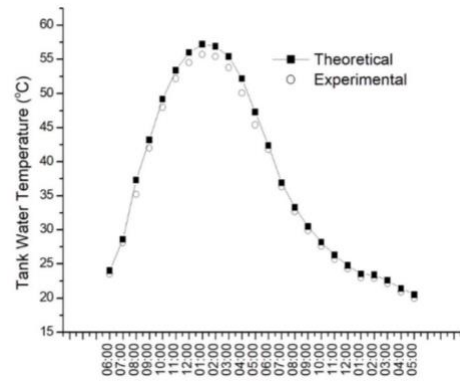


Fig.7. Theoretical and experimental basin water temperature of solar stills

Fig.8. Theoretical and experimental glass cover temperature of solar stills

Fig.9.



Theoretical and experimental exit water temperature of solar stills

Fig.10. Theoretical and experimental distillate output

It is seen from Figs. 7, 8, 9 and 10 that the experimental values are close to the theoretical values. Fig. 11 shows the time variation of tank water temperature the theoretical and experimental tank water temperature are close to each other.

Fig.11. Theoretical and experimental tank water temperature

2.4. Numerical Computations

Numerical computations have been performed for the climate of Jodhpur, India ($26^{\circ}14'20.21''\text{N}$ and $73^{\circ}1'27.51''\text{E}$). The plant's performance has been determined for a day in May and Jan. Hourly ambient temperature and solar radiation has been taken to determine hourly/daily and monthly yield from plant [1]. Initial temperature of water in basin of SS and in reservoir is taken equal to ambient temperature and the initial temperature of cover is taken 1° less than the basin temperature. Hourly yield is computed by the known initial values for 24 hours and the process is repeated till the steady state is reached. The various parameters used for computations is given in Table 2.

2.4.1. Effect of MFR of water in SSs

MFR of water flowing into the SS will affect the amount of distillate produced. The more MFR of water in SS will decrease the contact time of water with heated still basin, thus decreases the heating of water in solar still whereas at a low MFR the heating of water is more this happens in a conventional SSSS. But for the proposed plant

the effect of MFR is somewhat neutralized. The water from exit is collected in a reservoir provided, at higher MFR of water, the rate of mixing hot water coming from SS increases. To analyze the effect of MFR of water, computation has been performed at different MFR for a typical data set ($T_a = 30^\circ C$, $S = 500W / m^2$ and $v_a = 1.5m / s$). The MFR of water taken for computation is 0.0020kg/s, 0.0025kg/s, 0.0030kg/s, 0.0035kg/s and 0.0040kg/s). The result is as expected the hourly distillate output produced at MFR of 0.0020kg/s is 6.616L/m² when the MFR of water is increased to 0.0040kg/s the hourly output produced is 6.588L/m² (Fig.12). Result clearly shows that the MFR has very little effect on the output produced, with increase in MFR from 0.0020kg/s to 0.0040kg/s the decrease in hourly output is only 0.4%.

Table 2. Values of different parameters used in computations

$\alpha_g = 0.05$	$K'_3 = 0.034W / mK$
$\varepsilon_{eff} = 0.84$	$A_b = A_t = 0.20m^2 (16m^2)$
$\varepsilon_g = 0.94$	$U_t = U_s = 0.73W / m^2 K$
$\delta = 0.05m$	$c_w = 4190W / m^2 ^\circ C$
$L = 1m$	$\sigma = 5.64 \times 10^{-8} W / m^2 K$
$d = 1m$	$h_3 = 135W / m^2 K$ [63]

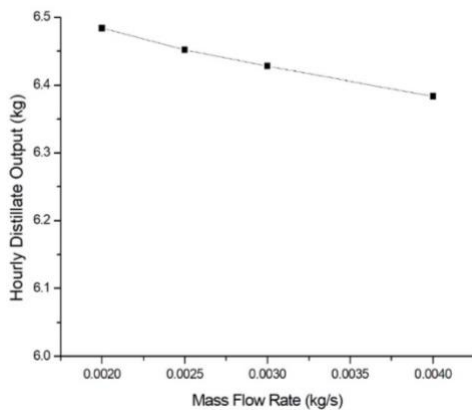
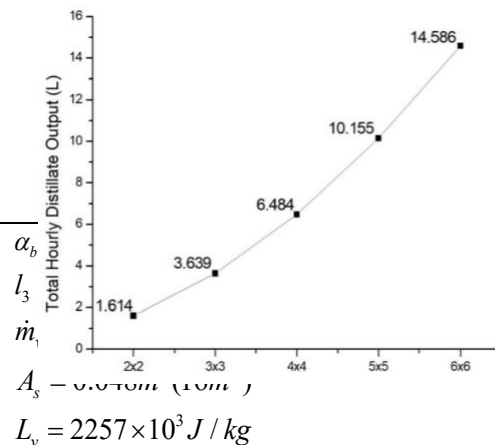


Fig.12. Effect of MFR on output of plant

2.4.2. Effect of plant size on hourly distillate output

In present work we considered small size plant of area 16m², for a typical data set as discussed in previous section we performed computations to determine the hourly output for different plant size viz. 4m² (2x2), 9m² (3x3), 16m² (4x4), 25m² (5x5) and 36m² (6x6). Size of reservoir is taken as discussed earlier, the corresponding size of reservoir considered for computations is taken as 12L, 19L, 24L, 30L and 36L, respectively. The depth of water in basin is taken as 0.5cm the other relevant parameters are same as discussed

earlier. The MFR of water is taken 0.0020kg/s constant for all plants. For a typical data set the hourly distillate output produced for 2x2, 3x3, 4x4, 5x5 and 6x6 plant size is 1.614L, 3.639L, 6.484L, 10.155L and 14.586L, respectively (Fig.13). The hourly distillate output produced increase to about 9 times when the plant size increases from 4m² (2x2) to 36m² (6x6). Output increases by increasing the plant size, the size of plant will depend on the demand of drinking water as well as the area available. The water from reservoir is pumped into the common inlet distribution pipe and fed evenly to different solar stills kept in a row (1st row). The water is further pumped into solar stills in different rows through interconnected pipes. For a given climatic condition technically the output produced by solar stills in a particular row will be same.



number of rows impacts the output produced. We ran simulations for various numbers of rows using a standard dataset and observed that beyond the third row, the output remained nearly constant (Fig. 14).

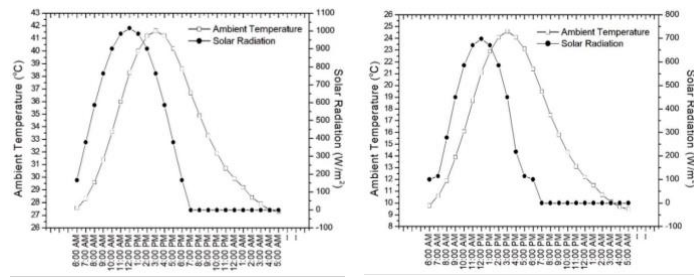


Fig.15. Ambient and solar radiation (a) Summer (b) Winter [1]

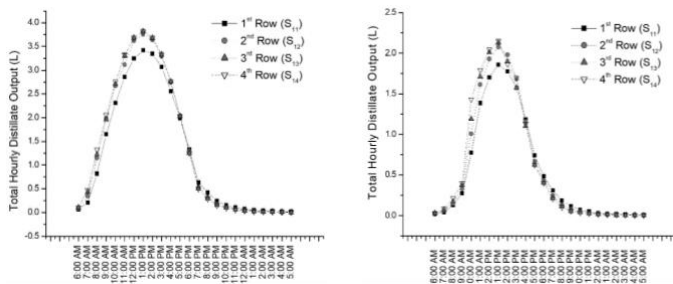
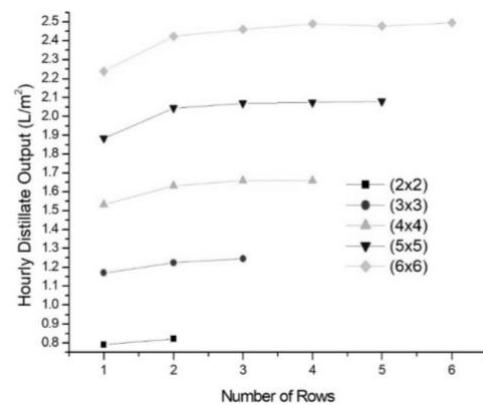


Fig.13. Total hourly distillate output produced by varying size of plant

Fig.14. Output in different rows (Effect of increasing number of rows)



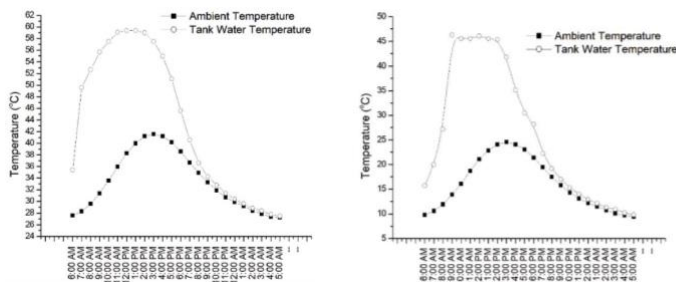
2.4.3. Performance of plant for summer & winter

Hourly/Daily distillate output of the proposed plant (4x4) has been determined for a day in May and Jan. for Jodhpur, India. The hourly solar radiation and ambient temperature for May and Jan. is shown in Figs.15a,15b. The depth of water in SS is taken as 0.5cm and MFR of water flowing has been taken as 0.0020kg/s. Total hourly distillate output of the proposed plant has been computed at different rows for May and Jan and shown in Figs. 16a & 16b.

Fig.16. Total hourly distillate output proposed by a SS in different rows (a) Summer (b) Winter

Fig.17. Transient tank water temperature (a) Summer (b) Winter

Total hourly distillate output of single SS for the 4th row is maximum, the output for the 3rd and 4th row is almost constant the same has been reflected in Fig.14 for typical data set. The maximum total hourly distillate output for 4th row for a SS in May is 3.82L at 1.00PM in afternoon due to maximum solar radiation received. The maximum hourly yield produced for a SS in Jan. from 4th row is about 2.152L at the same time in afternoon. Moreover, it is seen that for summer as well as winter the total distillate output produced is same for all the rows after 5PM due to unavailability of solar radiation. The temperature difference between cover and basin water of SS for different rows which is responsible for getting the output from SS has been computed for different rows and shown in Table 3. It is seen that the difference in temperature becomes almost constant after 3rd row. The transient temperature of water in reservoir is computed (Figs.17a & 17b). The temperature of water in reservoir is more than ambient temperature moreover the temperature of water increases with time till sunshine hours (4.00-5.00PM), thereafter the temperature drops



significantly. The maximum reservoir water temperature reached for May is 59.4°C at 1.00PM for Jan. it is 46.1°C at 1.00PM.

The cumulative daily distillate from the proposed plant has been computed for May and Jan. the output produced by plant has been compared from the output produced by a conventional single slope solar still (SSSS) plant of the same size. It is seen from Fig. 18, that the total daily output produced by the proposed plant is 122.3L and 55.2L for May and Jan. Whereas the daily distillate produced by SSSS plant for May and Jan. is 79.2L and 55.2L.

Fig.18. Daily distillate produced by proposed and conventional plant

The output of the proposed plant surpasses that of the conventional plant by 54.4% in May and by 72.2% in January. Figures 20 and 21 illustrate the monthly and annual distillate output from the plant. Figure 19 shows the number of clear days in different months for Jodhpur. We observe that the total monthly distillate output is highest (3667.2L) in May and lowest (1156.1L) in January. The total annual distillate output from the plant is 25528L, with the proposed plant producing approximately 60.9% more than the conventional SS plant annually.

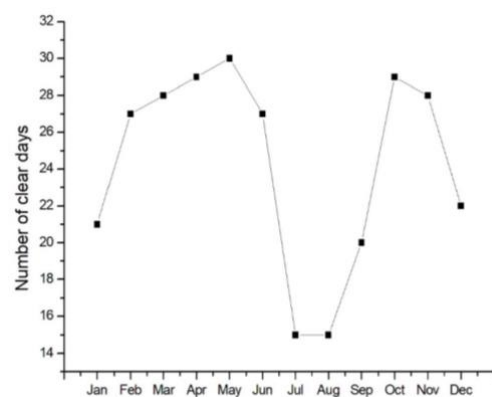
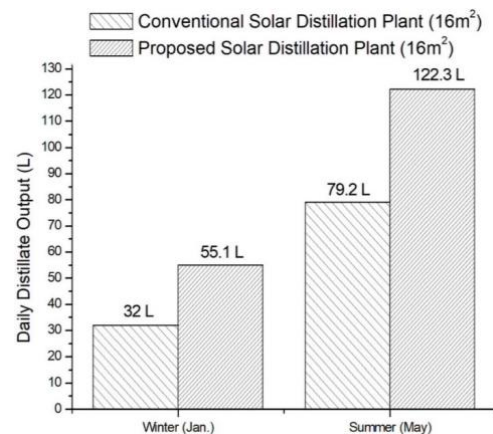


Fig.19. Clear days for different months for Jodhpur

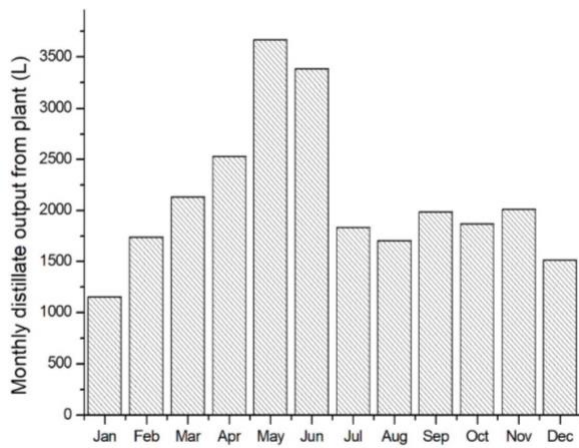


Fig.20. Total monthly distillate output produced from proposed plant

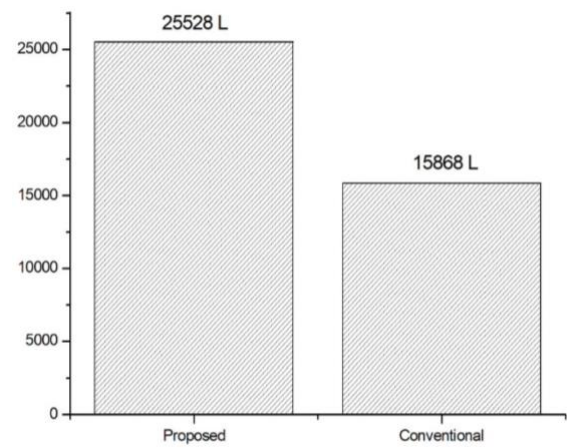


Fig.21. Total annual distillate output produced from plant

Table 3. Difference in temperature between basin water and glass cover in different rows

Time	Winter Month (Jan.)				Summer Month (May)			
	1 st Row	2 nd Row	3 rd Row	4 th Row	1 st Row	2 nd Row	3 rd Row	4 th Row
6:00 AM	2.7	3.9	4.6	5.2	3.7	5.3	6.3	6.8
7:00 AM	3.4	4.6	5.3	5.8	6.1	8.8	10.2	10.7
8:00 AM	9	8.9	9.6	9.8	14.1	15.5	14.8	15.1
9:00 AM	11.5	13.7	14.8	14.9	16.1	16.7	16.9	16.9
10:00 AM	19.7	20.8	22	22.2	16.2	16.7	16.8	16.8
11:00 AM	20.3	20.8	20.9	20.7	15.5	15.9	15.9	15.9
12:00 PM	19.1	19.7	19.8	19.8	14.5	14.8	14.9	14.9
1:00 PM	17.9	18.3	18.4	18.4	13.5	13.7	13.7	13.7
2:00 PM	16.2	16.7	16.3	17.2	12.5	12.7	12.8	12.8
3:00 PM	14.8	14.8	14.8	14.8	11.3	11.8	11.8	11.8
4:00 PM	12.2	11.7	11.4	11.4	10.8	10.8	10.8	10.8
5:00 PM	9.9	9.3	8.9	8.9	9.6	12.5	9.6	9.6
6:00 PM	8.7	8.1	7.9	7.8	8.1	7.7	7.7	7.6
7:00 PM	7	5.8	5.3	5	5.3	4.6	4.4	4.4
8:00 PM	5.5	4.4	3.9	3.6	4.9	4.2	3.9	3.8
9:00 PM	4.3	3.4	3	2.8	3.7	3.1	2.8	2.8
10:00 PM	3.5	2.8	2.5	2.2	3	2.5	2.4	2.1
11:00 PM	2.9	2.3	2	1.8	2.5	1.9	1.9	1.7
12:00 AM	2.4	1.9	1.6	1.5	2	1.6	1.4	1.3
1:00 AM	1.9	1.6	1.3	1.2	1.6	1.2	1.1	1.1
2:00 AM	1.7	1.4	1.2	1.1	1.4	1.2	1	1
3:00 AM	1.5	1.2	1	0.9	1.2	-0.7	1	0.8
4:00 AM	1.3	1	0.8	0.8	1.1	0.5	0.8	0.7
5:00 AM	1	0.8	0.7	0.6	0.8	0.4	0.6	0.5

3. Techno Economic Analysis

Following [64-68] we performed techno economic analysis to determine the cost of water produced by the proposed plant.

Assumptions are as follows: -

1. Solar stills are made by GRP material and inclined at an angle of 15°
2. Interest rate (i) is taken as 5% (subsidized interest rate offered by government sectors), 12% (offered by commercial banks) and 16% (interest rate offered in private borrowing)
3. Total life of plant (n') is considered as 25 years.
4. AMC is considered as 16% of the FAC [69]
5. Scarp value of GRP is assumed as Rs12/kg and iron are assumed to be Rs15/kg after 25 years. (Assumption is based on salvage values of present year)
6. The items cost is based on the local market price.
7. Life of pump (solar 20W) is considered as 6 years. two-time replacement is required in 25 years.
8. Cost of land is not included.
9. Plant size 16m² (4x4)

The total annual cost (TAC) of the plant will be given by

$$TAC = CC \times CRF + AMC - SV \times SFF \quad (33)$$

Capital recovery factor (CRF) and sinking fund factor (SFF) is given by,

$$CRF = \frac{i(1+i)^{n'}}{(1+i)^{n'} - 1} \quad (34)$$

$$SFF = \frac{i}{(1+i)^{n'} - 1} \quad (35)$$

Cost/L of water produced will be given by,

$$\text{Cost/Litre} = TAC / TAD \quad (36)$$

Various items used in plants is shown in Table 4 and the cost of scrap after 25 years (the total life span) of plant is shown in Table 5. Rs/L of the water produced has been computed considering rate of interest as 5%, 12% and 16% and shown in Fig.22. The cost of water produced is between Rs 0.30/L (0.0036US\$) to Rs0.70/L (0.0085US\$).

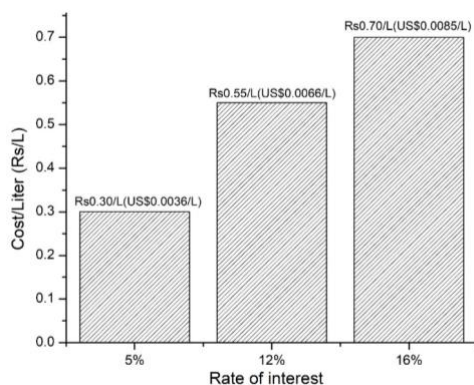


Fig.22. Cost/Litre of water produced from proposed plant

3.1. Computation of Payback Period of Plant (n_p)

The time needed to recover the capital cost invested in the project is known as payback period. For the proposed plant payback time has been computed by considering the rate of interest on capital cost as 5%, 12% and 16%. The selling price of the distilled water produced is taken as Rs10/L, Rs12/L and Rs20/L. The payback period will be given by [6],

$$n_p = \frac{\ln\left[\frac{CF}{CF - P_s \times i}\right]}{\ln(1+i)}$$

The cash flow CF will be given by,

$$CF = TAD \times SP$$

$$P_s = \text{Initial cost of plant}$$

It is seen from Fig. 23, that the interest rate on capital cost is not affecting the payback period significantly. When selling price of water is taken as Rs 10/L the payback period of plant is 141, 93 and 70 days at interest rates of 5%, 12% and 16%, respectively. For SP of Rs 15/L the payback period will be 147, 97 and 72 days and when sold at Rs 20/L the payback period of plant will be 151, 100 and 75 days at interest rates of 5%, 12% and 16%.

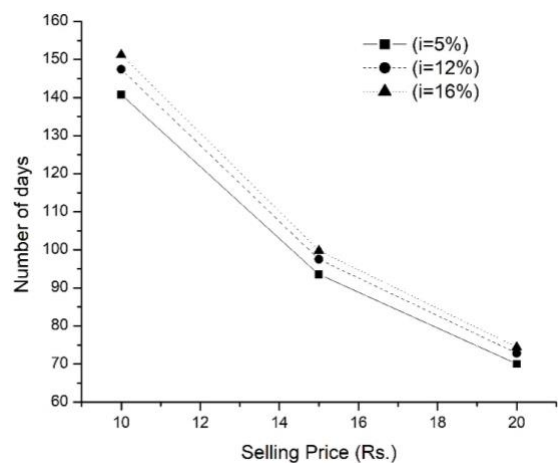


Fig.23. Payback period for investment

Table 4. Cost of various items in the proposed plant (16m²) as per local market

Item	Material	Cost	Rs
Solar Still (C _{ss}) (1m ² basin area for 15° inclination)	1. GRP Body (5mm)	$C_{ss}=A_t \times W_{sp} \times R_{GRP}$ A_t = Total area of SS = 2.14m ² W_{sp} = Specific weight= 6.3kg/m ² R_{GRP} = Cost/kg=Rs300/kg	4044.60
	2. Glass (2mm)	$C_g=A_g \times R_g$ A_g = Area of glass =1m ² R_g = Cost/m ² = Rs320/m ²	320
	3. Putty	$C_{pu}=M_{pu} \times R_{pu}$ M_{pu} = Mass of putty = 3kg R_{pu} = Cost/kg= Rs20/kg	60
	4. Iron stand (Angle 32 x 32 x 3 mm)	$C_{st}= M_{st} \times R_{st}$ M_{st} = Mass of iron stand= 10kg R_{st} = Cost/kg= Rs40/kg	400
	5. Mis.	Labor cost+ fitting & glass cutting	500
	Total cost of single SS (C_{ss})		5324.60
	1. Solar pump*	$C_{sp}=@1000$	3000*
	(20W)		
	2. PVC pipe (0.5'' dia.)	$C_{pvc}=L_p \times R_{pvc}$ L_p = Total length of pipe = 40m R_{pvc} = Cost/m=Rs50/m	2000
Other items in plant (C _{oi})	3. Insulation (Rubber)	$C_{ri}= L_{ri} \times R_{ri}$ L_{ri} = Total length of pipe = 40m R_{ri} = Cost/m=Rs67/m	2680
	4. Reservoir tank (MS plate 2mm)	$C_{rt}=A_{rt} \times W_{rt} \times R_{rt}$ A_{rt} = Total area of tank = 0.6m ² W_{rt} = Specific weight= 15.7kg/m ² R_{rp} = Cost/kg=Rs40/kg	376.8
	5. Valve	$C_{va}=@Rs110$	220 (2 valve)
	6. Distillate storage tank	$C_{dst}=@200L$	1200
	7. Labour	Labour & transportation	500
	Total cost of other items (C_{oi})		9976.80
	Total cost of plant (16m²)		95170.40
	(CC= n C_{ss} +C_{oi})		

* Replacement in every 6 years

6. Comparison of the proposed technology with some existing technologies

To compare the proposed work with some other relevant

Table 5. Expected cost of salvage value of various items after 25 years

Components	Quantity	Salvage value (Rs)
GRP body	135.04kg	1620.48 (@ Rs12/kg)
Iron stand	160kg	2400 (@Rs15/kg)
Glass	0	0
Solar pump	0	0
Reservoir tank	10kg	150 (@Rs15/kg)
Total salvage value		4170.48

4. Results

The proposed Closed Loop Single Slope Solar Still (CLSSS) significantly outperforms the conventional single slope solar distillation plant. It requires less area to produce the same amount of distillate output. Key findings from the study are as follows:

1. The mathematical model of the proposed CLSSS has been developed and validated through experiments conducted in the climate of Raipur, Chhattisgarh, India.
2. The mass flow rate (MFR) of water entering the solar still has a minimal impact on distillate output. For a 16m² (4x4) plant under typical conditions (ambient temperature of 30°C, solar radiation of 500W/m², and wind speed of 1.5m/s), increasing the MFR from 0.0020kg/s to 0.0040kg/s results in only a 0.4% decrease in hourly output.
3. With the same typical parameters, increasing the plant size from 4m² to 36m² increases the hourly distillate output by nine times.
4. In Jodhpur, India, a 16m² (4x4) plant produces a total daily output of 122.3 liters in May and 79.2 liters in January.
5. The CLSSS plant generates 54.4% and 72.2% more output than the conventional single slope solar still (SSSS) in May and January, respectively.
6. The annual distillate output for a 16m² CLSSS plant in Jodhpur is 25,528 liters.
7. This annual output is 60.9% higher than that of the conventional SSSS plant.
8. To achieve the same distillate output as the proposed CLSSS plant, a conventional SSSS plant would require 26m², which is 62.5% more area.
9. The cost of water produced ranges from Rs 0.30/L (\$0.0036) to Rs 0.70/L (\$0.0085), assuming a capital cost interest rate between 5% and 16%.
10. The payback period for the installed plant ranges from 70 to 151 days, with the selling price of water set between Rs 10/L and Rs 20/L.

works a comparison table (Table-6) has been provided. It is

seen that the proposed work is found to be an economical and feasible option to meet drinking water demand. The cost of water produced in this work is Rs. 0.30/L (0.0036 US\$) to Rs. 0.70/L (0.0085 US\$) and the payback period is 70 to 151 days.

6. Conclusions

The proposed plant could be an excellent choice for a tiny town in need of drinking water because it requires less space and can be installed on rooftops. The total cost of installing plant (16m²) is less than 1 lakh (Indian rupee). The cost of water produced is between Rs 0.30/L (0.0036US\$) to Rs 0.70/L (0.0085US\$) when the rate of interest on capital cost is assumed between 5% to 16% respectively. The cost of investment can be recovered between 70 days to 151 days.

7. Future Recommendations

The primary objective of this study was to design and develop an economical solar distillation system to meet the drinking water needs of a small to medium-sized family or a small rural community in India. The closed loop single slope solar distillation plant (CLSSS) proposed in this work has proven suitable for delivering a reasonably good amount of water to address this demand. Based on the findings and observations, the following recommendations for future work are suggested:

1. Mixing nanomaterials with water (nanofluid) will definitely increase the water temperature, which will help enhance the overall water production from the proposed system.
2. It is strongly recommended to further investigate the scaling, fouling, and quality of the fresh water, especially with high salinity sources such as seawater desalination.
3. A wick type of solar still performs better than the conventional single slope solar still. Designing a plant

containing a wick type solar still operating in a closed loop is expected to perform better than the proposed closed loop single slope solar still plant.

Table 6. Comparision of this work with previous work

Ref.	Solar still (SS) type	η %	Yield (L/m ² /day)
Rai & Tiwari [24]	S.S + FPC	-	6.6 L/m ² /day
Shehata et al. [31]	SS+PCM+ evacuated solar collector	-	5.11 L/m ² /day
Madhhachi & Smaisim [44]	Square pyramid SS	60%	2.2 L/m ² /day
Sharshir et al.[45]	Pyramid SS+ nanofluid+ V absorber wick	60.5%	5 L/m ² /day
Kabeel et al.[46]	Pyramid still coated with TiO ₂ nano-black paint	-	6.60 L/m ² /day
Somwanshi & Shrivastava [62]	Closed loop inclined wick solar still (CLIWSS)	64.1%	8.432 L/m ² /day (May)
		(May)	3.618 L/m ² /day (Dec)
Present work	CLSSS Plant 16m ²	-	7.6 L/m ² /day (May)
			3.4 L/m ² /day (Jan)
			(1 cm depth)

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N/A

Author Contributions

All authors were responsible for the conceptualization, validation, resources, data curation, software development, and project administration. They jointly contributed to the methodology, formal analysis, investigation, original draft preparation, review and editing, visualization, supervision, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Nomenclatures

A_c	Area of basin	m^2
A_t	Area of upper face of storage tank	m^2
A_b	Area of lower face of storage tank	m^2
A_s	Area of side face of storage tank	m^2
c_w	Specific heat of water	$J kg^{-1} K^{-1}$
d	Width of solar still	m
ε_{eff}	Effective emissivity	
ε_g	Emissivity of glass cover	
ε_w	Emissivity of water	
h_{ci}	Convective heat transfer coefficient between water and glass cover	$W / m^2 K$
h_{ri}	Radiative heat transfer coefficient between water and glass cover	$W / m^2 K$
h_{ei}	Evaporative heat transfer coefficient between water and glass cover	$W / m^2 K$
h_{co}	Convective heat transfer coefficient between glass and air	$W / m^2 K$
h_{ro}	Radiative heat transfer coefficient between glass and air	$W / m^2 K$
h_3	Heat transfer coefficient between basin liner and water	$W / m^2 K$
h_4	Convective heat transfer coefficient between bottom insulation and ambient air	W / m^2
i	Annual rate of interest	
K'_3	Thermal conductivity of insulation material	$W m^{-1} K^{-1}$
l_3	Width of insulation	m
L_v	Latent heat of vaporization of water	J / kg
L	Length of solar still	m
$\dot{m}_w$	Mass flow rate of water flowing inside basin	kg / s

$\dot{m}_{ews}$	Distillate output produced per second	kg / s
M_{wt}	Mass of water in storage tank (reservoir)	kg
$\dot{m}_{ewh}$	Hourly distillate output produced	kg / h
n_s	Number of stills in last row of plant	
P_w	Saturated vapor pressure at water temperature	N / m^2
P_g	Saturated vapor pressure at glass temperature	N / m^2
$\dot{Q}_u$	Rate of heat added by solar still into tank	W
$\dot{Q}_m$	Rate of heat taken by make-up water	W
$\dot{Q}_r$	Rate of heat loss from top of storage tank	W
$\dot{Q}_s$	Rate of heat loss from sides of storage tank	W
$\dot{Q}_b$	Rate of heat loss from bottom of storage tank	W
$S(t)$	Solar radiation	W / m^2
T_g	Temperature of glass cover	$^{\circ}C$
T_w	Temperature of water in basin	$^{\circ}C$
T_a	Ambient temperature	$^{\circ}C$
T_b	Temperature of basin liner	$^{\circ}C$
T_{w0}	Initial water temperature	$^{\circ}C$
T_{wt}	Tank (reservoir) water temperature	$^{\circ}C$
T_{wl_n}	Exit water temperature from n^{th} row of plant	$^{\circ}C$
U_s	Side loss coefficient of the storage tank	$W m^{-2} K^{-1}$
U_t	Top loss coefficient of the storage tank	$W m^{-2} K^{-1}$
U_b	Bottom loss coefficient of the storage tank	$W m^{-2} K^{-1}$
v_a	Velocity of air	m / s
α_g	Absorptivity of glass cover	
σ	Stefans-Boltzmann constant	$W / m^2 K^4$
ρ_w	Density of water	kg / m^3

Abbreviations

CLSSSS	Closed loop single slope solar still
SS	Solar still
SSSS	Single slope solar still
MFR	Mass flow rate
TAC	Total annual cost
TAD	Total annual distillate produced
CC	Capital cost
CRF	Capital recovery factor
AMC	Annual maintenance cost



SV	Salvage value
SFF	Sinking fund factor
CF	Cash flow
C_p	Payback period
FPC	Flate plate collector
ISS	Inclined solar still